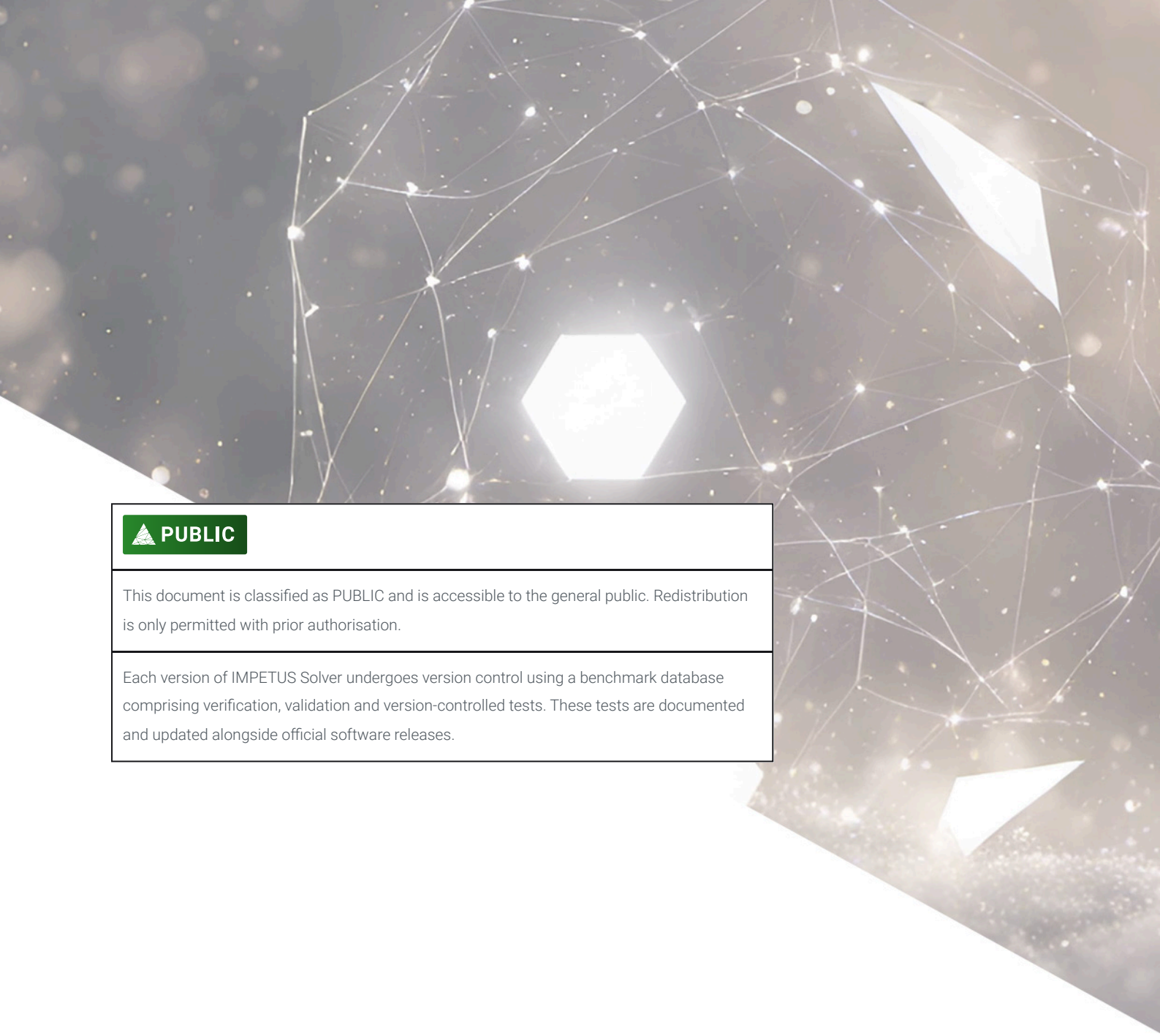


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Each version of IMPETUS Solver undergoes version control using a benchmark database comprising verification, validation and version-controlled tests. These tests are documented and updated alongside official software releases.

Verification - Calibrated Explosives

Documentation

Version 11.1.0

September 28, 2026

IMPETUS
driving precision

Document revisions:

Revision	Date	Comments
4	2025-03-21	Added: Simulations using FE addded to plots
3	2020-10-20	Added: LX-14-0
2	2017-09-05	Added: Tetryl, LX-10-1, PBXN-9010, NSP-711
1	2017-02-02	Added: ANFO, PBXN-110, MCX-6100
0	2017-01-30	First publication

Verification - Calibrated Explosives

Introduction

This document presents the verification of the calibrated explosives available in the software.

There are currently 16 calibrated explosives available in the software and additional compositions are added on request from users.

Version control

The tests presented in this document are subjected to version control, meaning that the models are run and evaluated prior to release of a new solver. This document is updated in conjunction with official releases of the software.

Verification - Calibrated Explosives

Calibrated explosives

The following explosives are available in both the Discrete particle (DP) module and the Computational Fluid Dynamics (CFD) module:

ANFO	C4
COMP. A-3	COMP. B (grade A)
HMX	LX-10-1
LX-14-0	MCX-6100
NSP-711	OCTOL 78-22
PBXN-110	PBXN-9010
PETN	TETRYL
TNT	m/46

Calibrated explosives are included in an analysis with the command *PARTICLE_HE or *CFD_HE.

Modelling of explosives in the DP module

Explosives are defined by the following parameters:

ρ_0 - Density of undetonated composition

e_0 - Energy per unit volume

γ - Fraction between C_p and C_v at zero co-volume (ideal gas regime)

v - Co-volume at $\rho = \rho_0$

D - Detonation velocity

ρ_0, e_0 and D are found in literature whereas γ and v must be calibrated to the DP module. The calibration was done with the model described in section "Controlled expansion test". Parametric values used for the calibrated explosives are presented in Table 1.

Explosive	$\rho_0\ [kg/m^3]$	$e_0\ [GPa\ m^3/m^3]$	$\gamma\ [-]$	$v\ [-]$	$D\ [m/s]$	ref
ANFO	782	2.9	1.280	0.235	5000	2
C4	1601	9.0	1.270	0.347	8193	1
COMP. A-3	1650	8.9	1.442	0.259	8300	1
COMP. B (grade A)	1717	8.5	1.428	0.270	7980	1
HMX	1891	10.5	1.345	0.334	9110	1
LX-10-1	1865	10.4	1.606	0.211	8820	1
LX-14-0	1835	10.2	1.576	0.222	8800	1
MCX-6100	1710	7.6	1.404	0.262	7486	3
NSP-711, m/46	1500	7.05	1.315	0.308	7680	4
OCTOL 78-22	1821	9.6	1.598	0.210	8480	1
PBXN-110	1672	8.7	1.375	0.283	8330	5
PBXN-9010	1787	9.0	1.451	0.276	8390	1
PETN	1770	10.1	1.621	0.188	8300	1
TETRYL	1730	8.2	1.442	0.265	7910	1
TNT	1630	7.0	1.299	0.315	6930	1

Table 1. Explosives and associated values of the parameters.

The object "Controlled expansion test" available on IMPETUS Market allows for users to calibrate other explosives to the DP module.

Modelling of explosives in the CFD and FE modules

Explosives are defined by the following parameters:

ρ_0 - Density of undetonated composition

e_0 - Energy per unit volume

D - Detonation velocity

A, B, R_1, R_2 and ω - JWL coefficients

ρ_0, e_0 and D are set in accordance with Table 1, whereas the parameters for the Jones-Wilkins-Lee (JWL) equation of state are set as presented in Table 2.

The JWL equation of state is defined as:

$$P = A\left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega e_0}{V}$$

P - Pressure

V - Ratio volume detonation products and volume undetonated explosive

Explosive	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	ref
ANFO	75.2	-0.82	4.1	1.25	0.44	2
C4	609.8	12.95	4.5	1.4	0.25	1
COMP. A-3	611.3	10.65	4.4	1.2	0.32	1
COMP. B (grade A)	524.2	7.68	4.2	1.1	0.34	1
HMX	778.3	7.07	4.2	1.0	0.30	1
LX-10-1	880.7	18.36	4.62	1.32	0.38	1
LX-14-0	826.1	17.24	4.55	1.32	0.38	1
MCX-6100	759.8	7.0	4.88	1.10	0.35	3
NSP-711, m/46	759.9	12.56	5.1	1.5	0.29	4
OCTOL 78-22	748.6	13.38	4.5	1.2	0.38	1
PBXN-110	950.4	10.98	5.0	1.4	0.40	5

Explosive	A	B	R_1	R_2	ω	ref
PBXN-9010	581.4	6.8	4.1	1.0	0.35	1
PETN	617.0	16.93	4.4	1.2	0.25	1
TETRYL	586.8	10.67	4.4	1.2	0.28	1
TNT	371.2	3.23	4.15	0.95	0.30	1

Table 2. Explosives and associated values of the JWL coefficients.

Controlled expansion test

The model consists of the explosive under consideration, detonated inside a confined volume as visible in Figure 1. The confined volume is increased gradually in a prescribed manner from 1.0 to 5.0 times the volume of the undetonated charge. A sensor is positioned in the explosive and the pressure in this sensor is compared to the pressure obtained from the JWL equation of state.

Parameter γ and v are calibrated so that the pressure in the sensor match the pressure from the JWL equation of state for the investigated expansion.

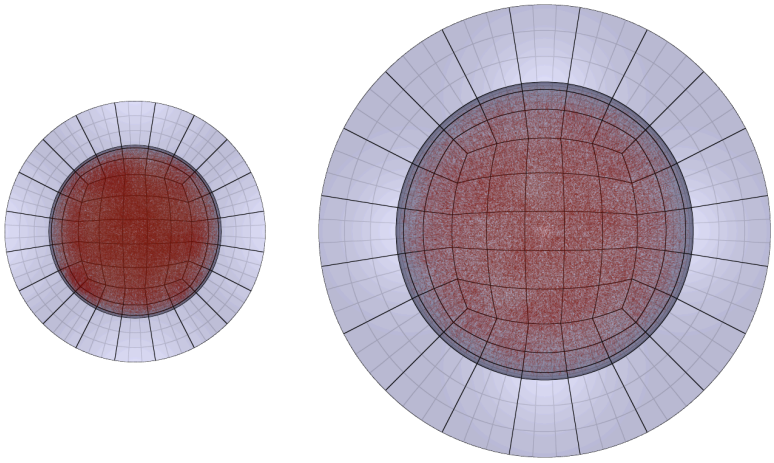


Figure 1. The confined volume is increased gradually from the initial state (to the left) to the final state (to the right).

The pressure from the sensor and the pressure obtanied from the JWL equation of state for all calibrated explosives, modeled using both the DP module and CFD module are presented in Figure 2 - 16. The left plot in these Figures shows the pressure with linear scale whereas the right plot shows the pressure with logarithmic scale.

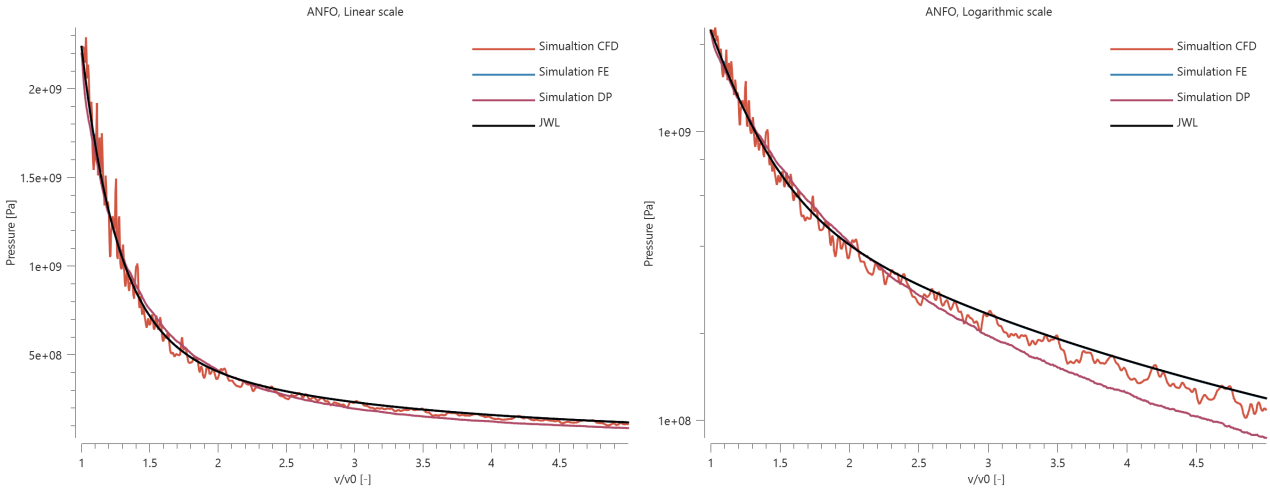


Figure 2. Results from the controlled expansion test with calibrated ANFO.

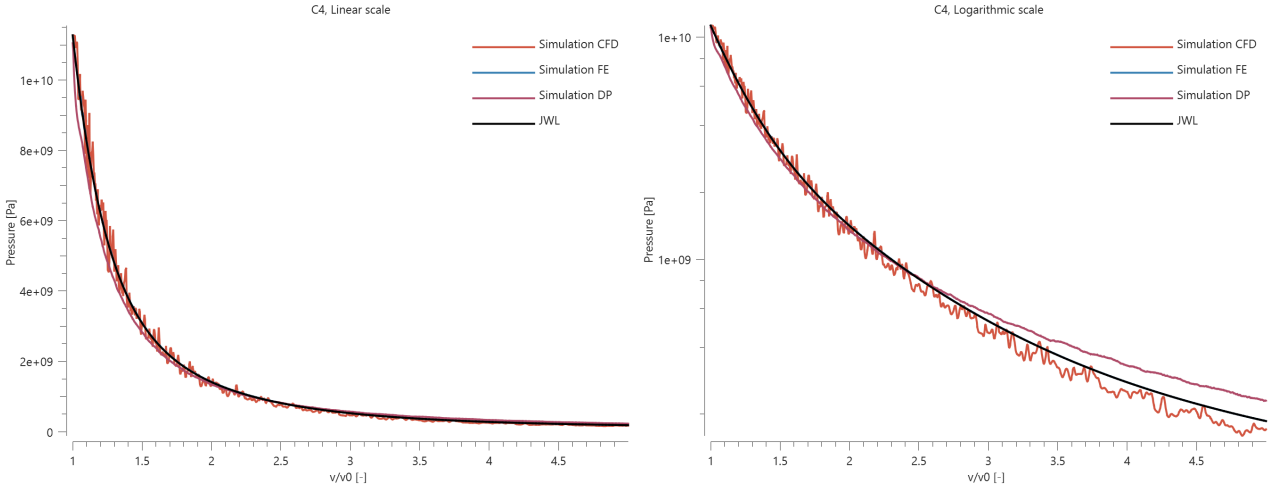


Figure 3. Results from the controlled expansion test with calibrated C4.

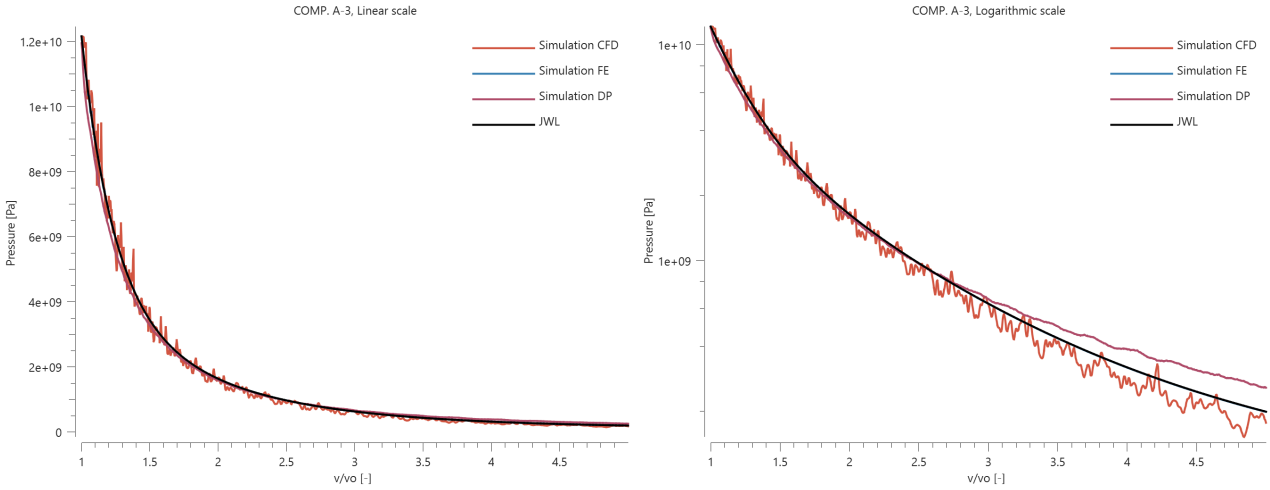


Figure 4. Results from the controlled expansion test with calibrated COMP. A-3.

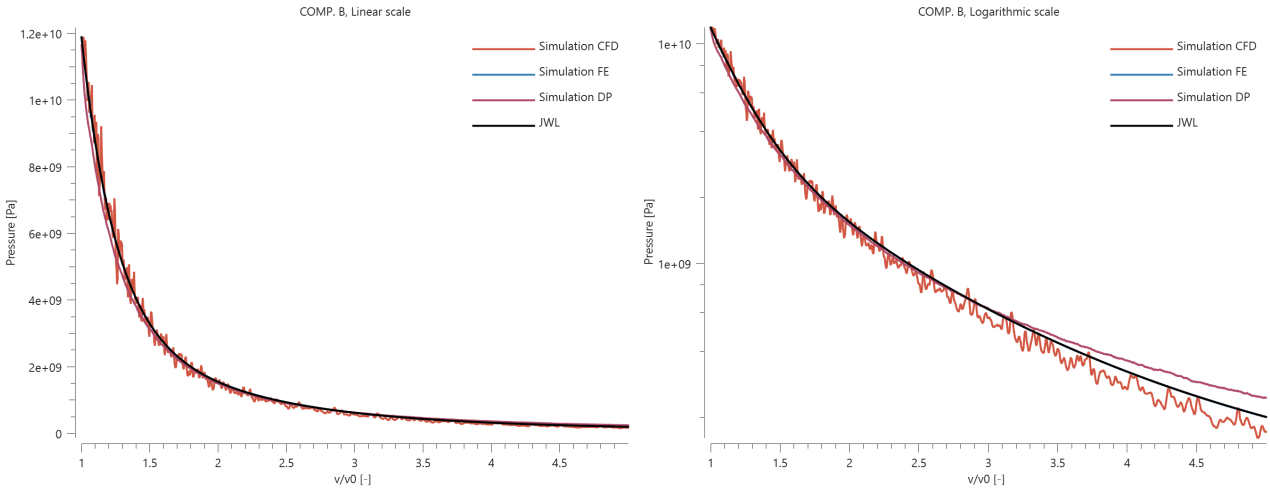


Figure 5. Results from the controlled expansion test with calibrated COMP. B (grade A).

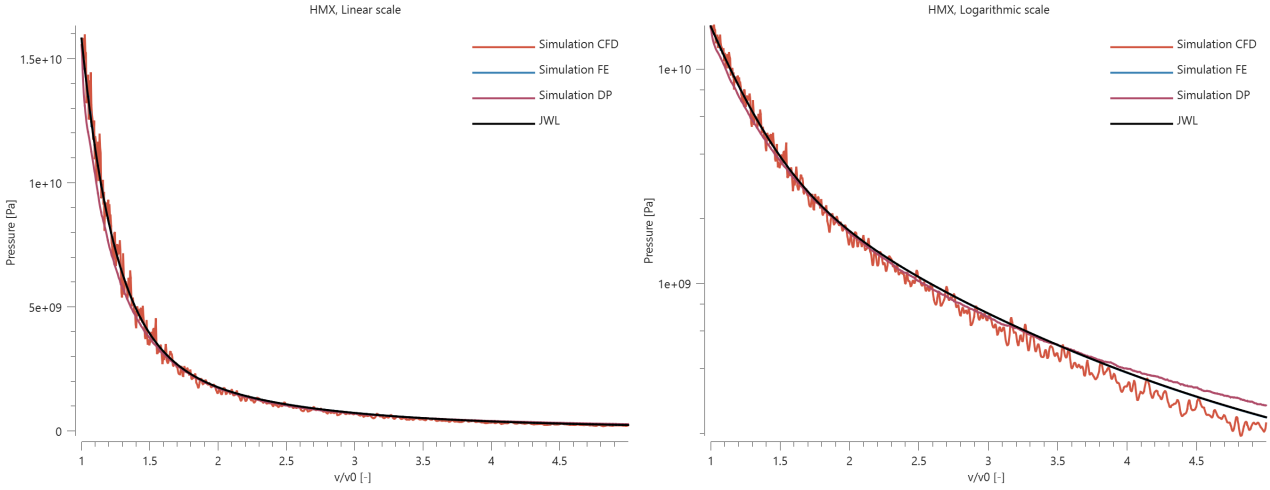


Figure 6. Results from the controlled expansion test with calibrated HMX.

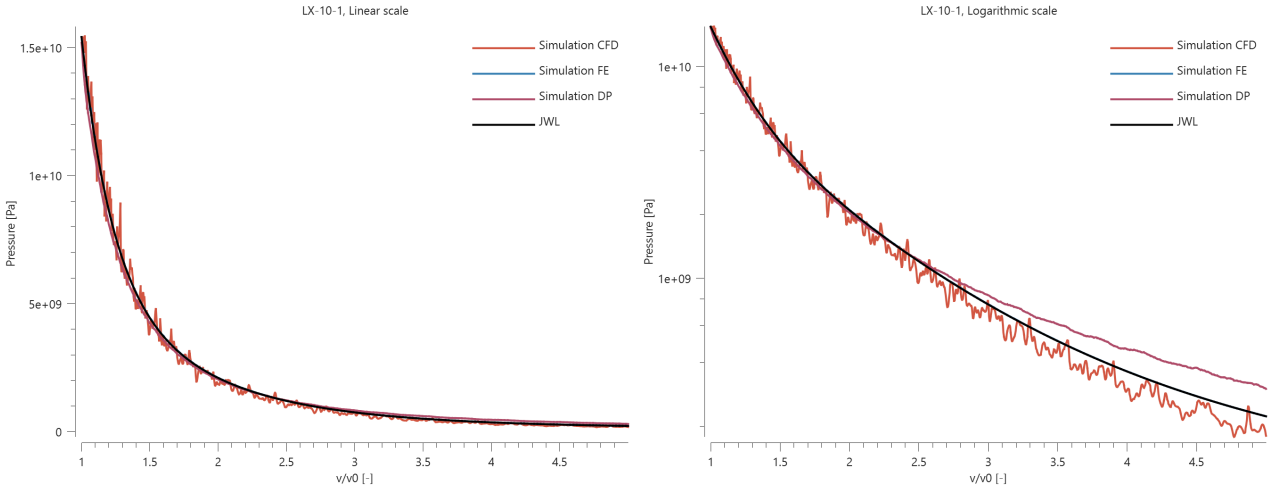


Figure 7. Results from the controlled expansion test with calibrated LX-10-1.

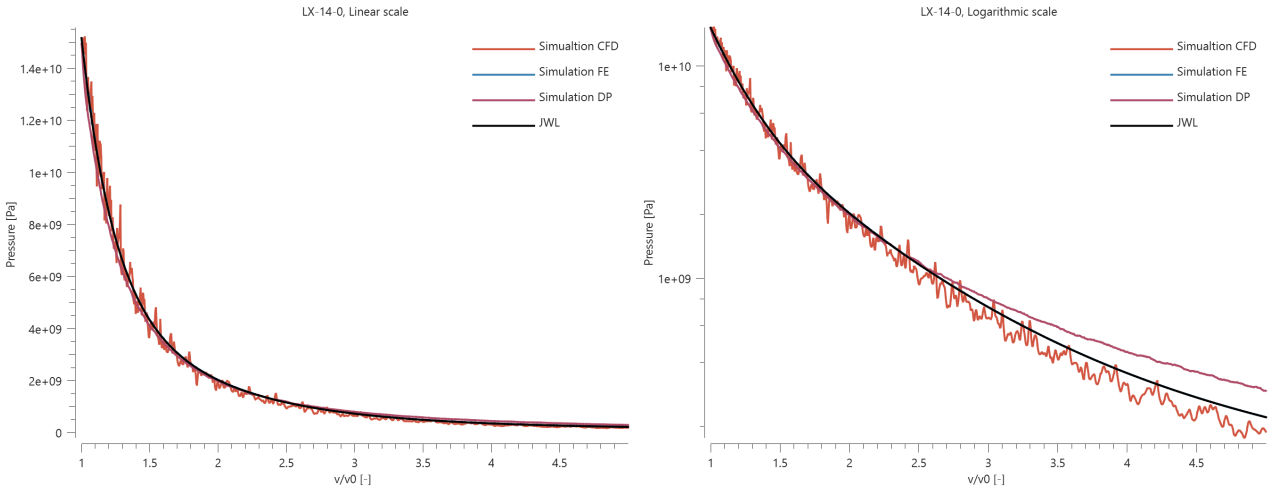


Figure 8. Results from the controlled expansion test with calibrated LX-14-0.

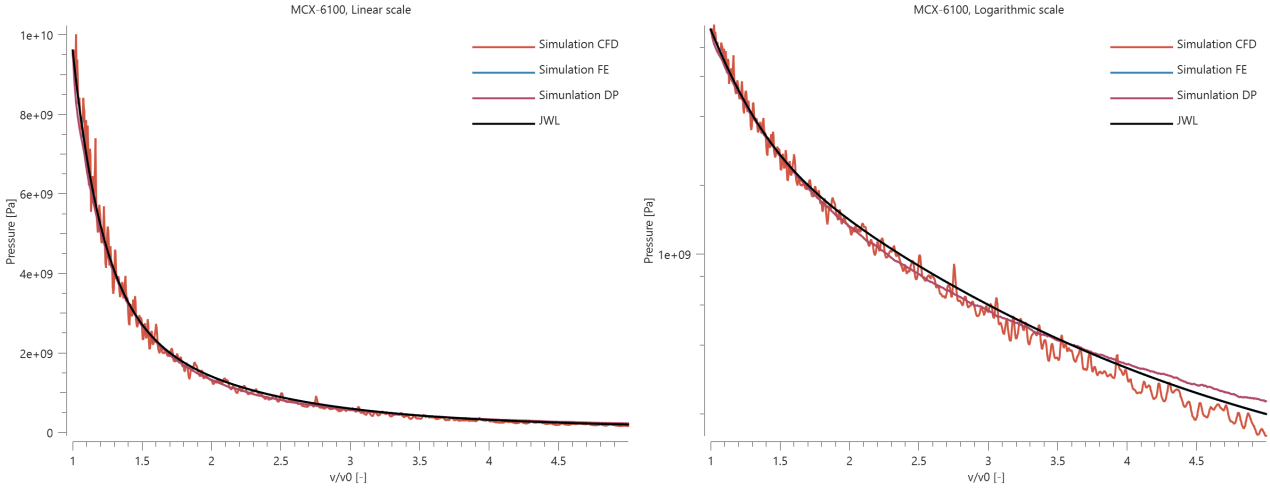


Figure 9. Results from the controlled expansion test with calibrated MCX-6100.

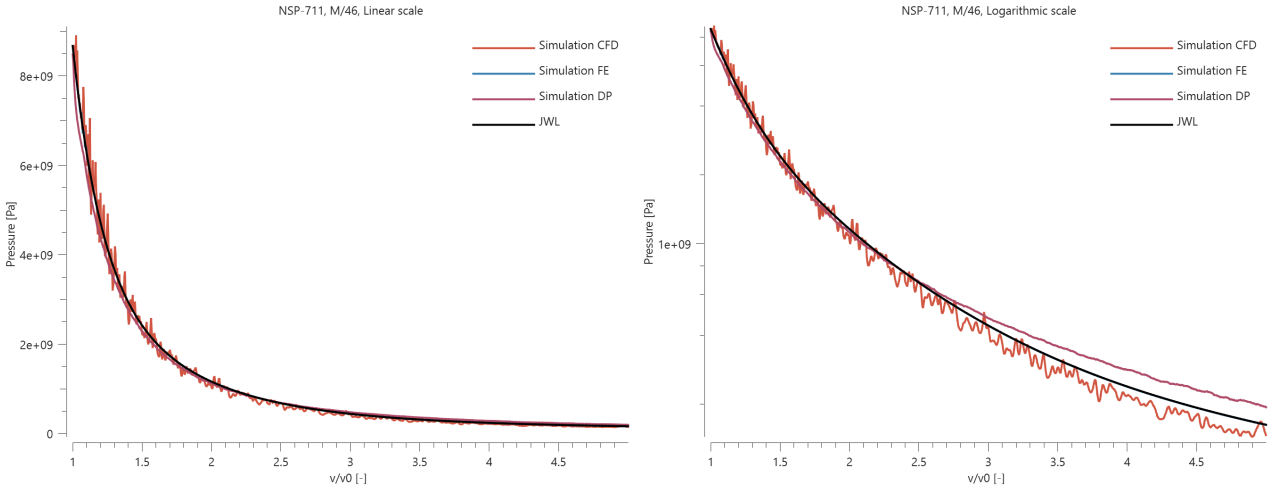


Figure 10. Results from the controlled expansion test with calibrated NSP-711, m/46.

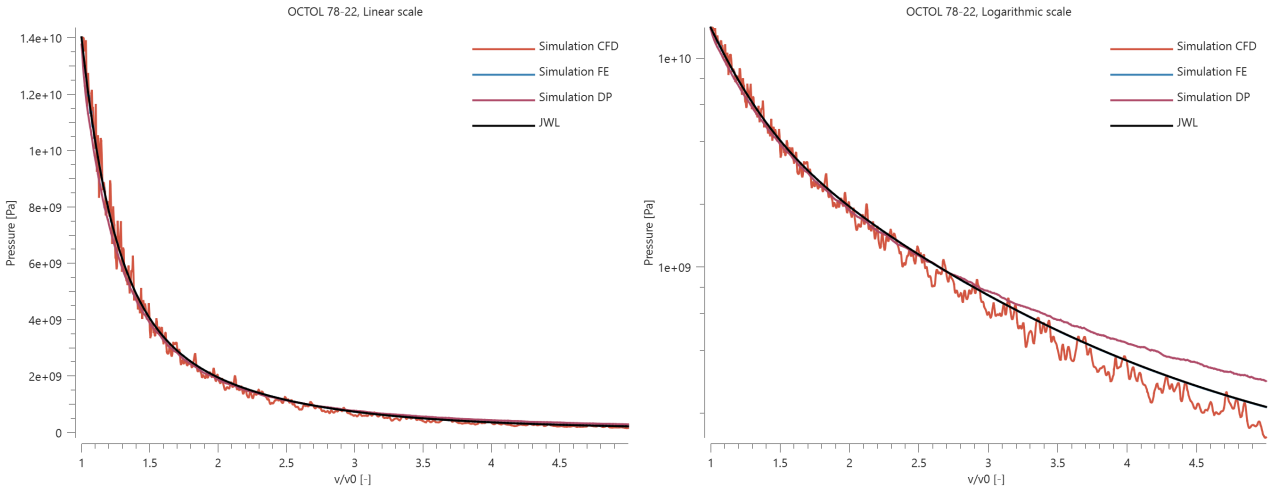


Figure 11. Results from the controlled expansion test with calibrated OCTOL_78-22.

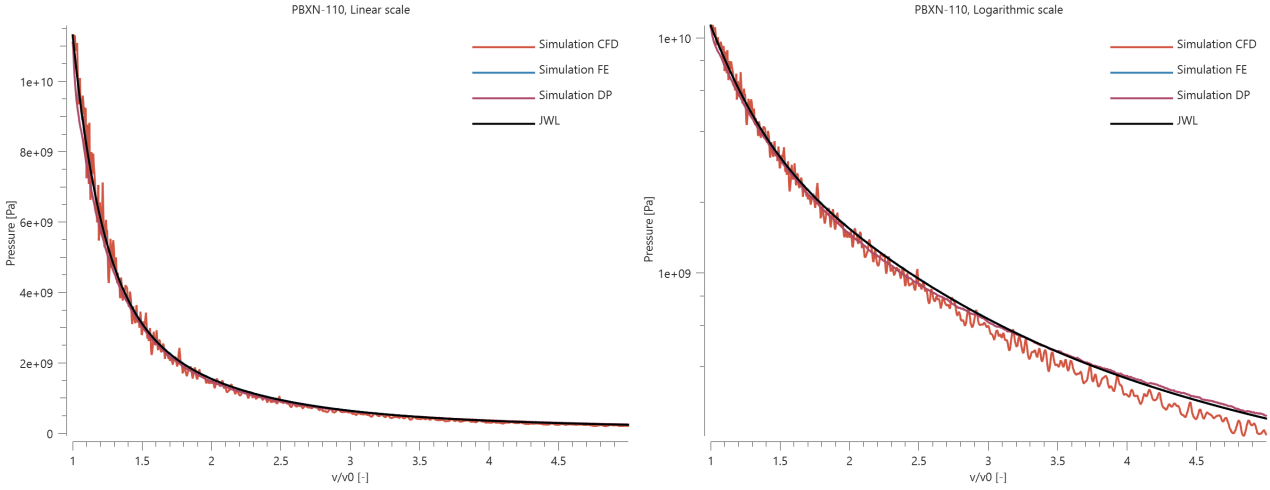


Figure 12. Results from the controlled expansion test with calibrated PBXN-110.

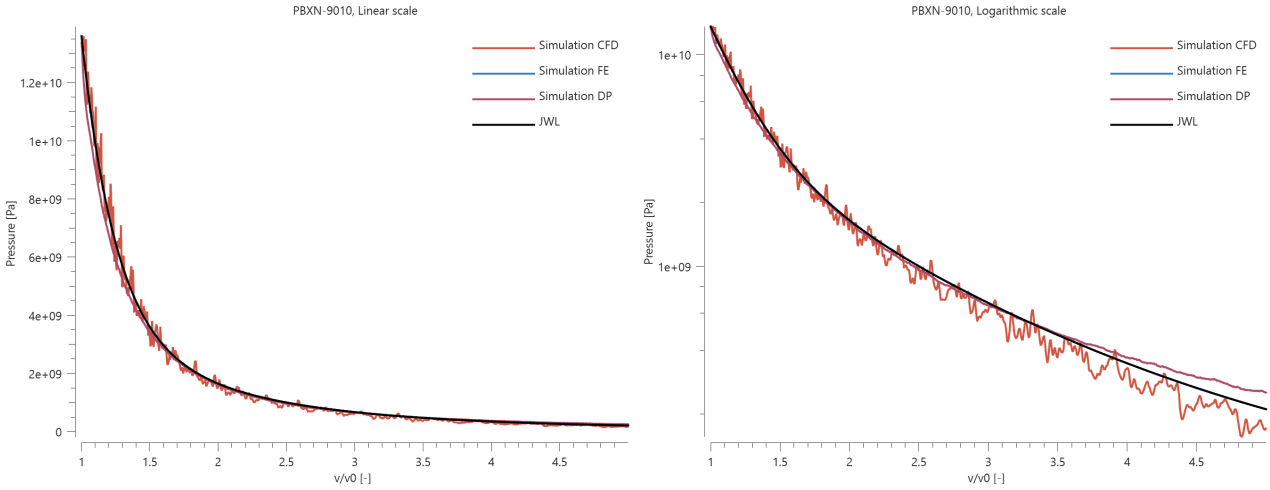


Figure 13. Results from the controlled expansion test with calibrated PBXN-9010.

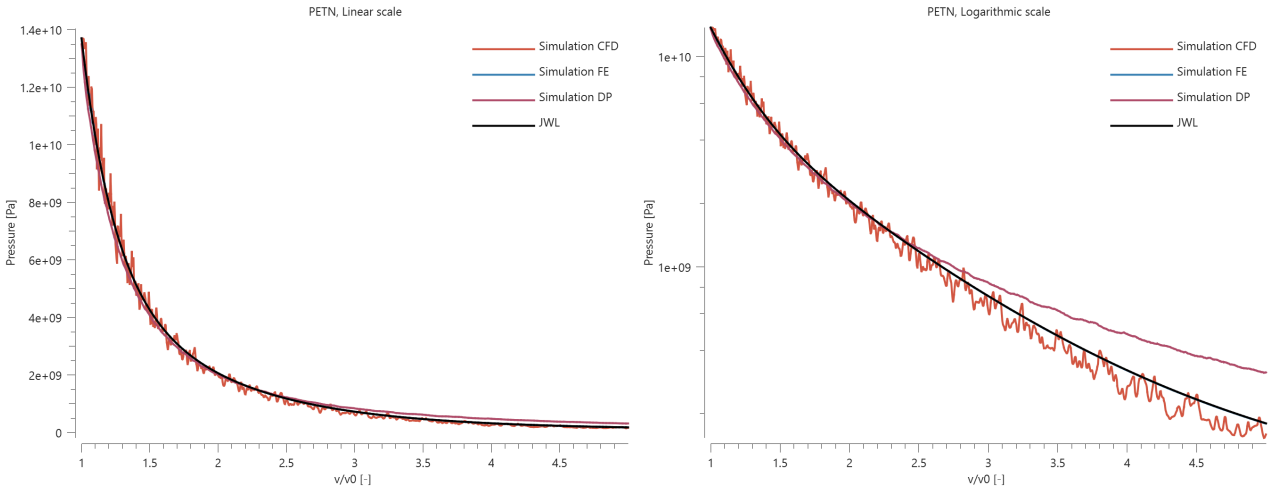


Figure 14. Results from the controlled expansion test with calibrated PETN.

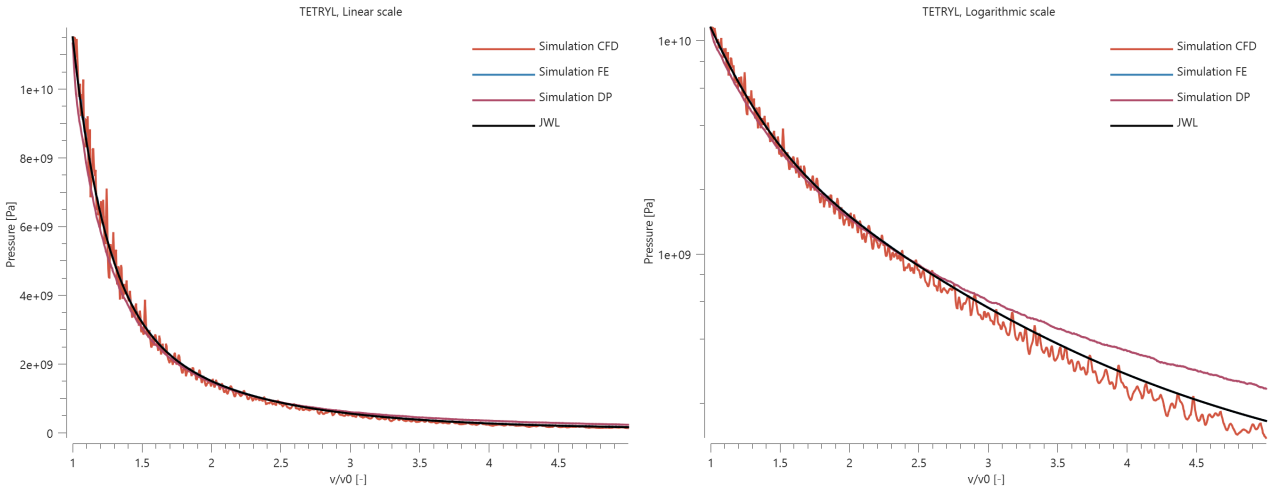


Figure 15. Results from the controlled expansion test with calibrated TETRYL.

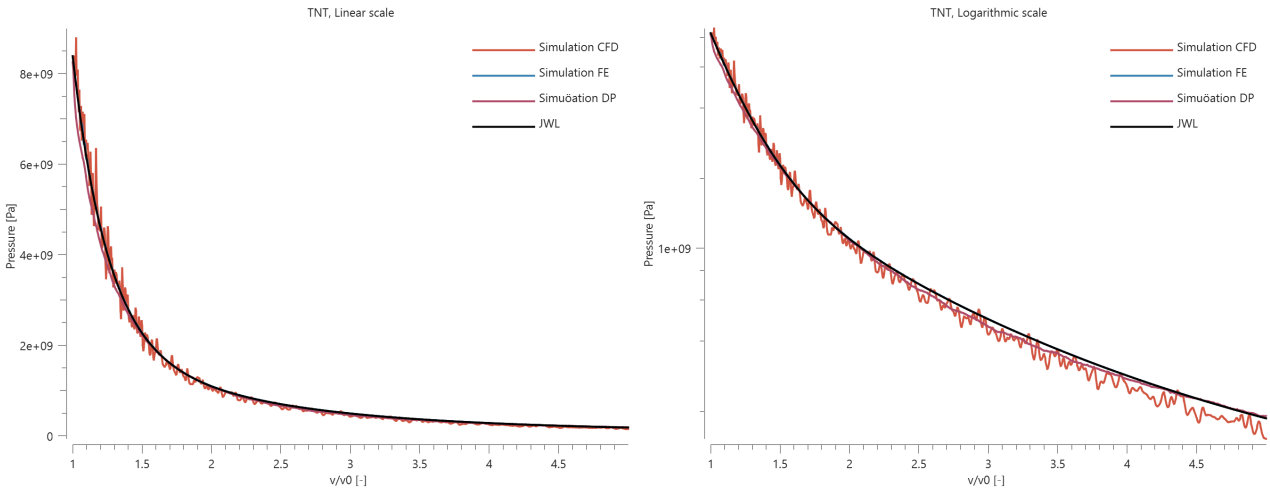


Figure 16. Results from the controlled expansion test with calibrated TNT.

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[2] - L. Penn, F. Helm, M. Finger, E. Lee, Determination of Equation-of-State Parameters for Four Type of Explosive, Lawrence Livermore Laboratory, 1975.

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[4] - A. Helte, J. Lundgren, H. Örnhed, M. Norrefeldt, Evaluation of performance of m/46, FOI-R--2051--SE, 2006.

[5] - O. Ayisit, The influence of asymmetries in shaped charge performance, International Journal of Impact Engineering, volume 35, pages: 1399 - 1404, 2008.

TESTS

This benchmark is associated with 16 tests.